MICROWAVE SANITIZATION OF TEXTILES

by

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INTRODUCTION

Since early history, scholars have hypothesized that disease was spread by invisible "seeds" which were transmitted from person to person or from inanimate objects. This idea is exemplified in the poem "De Rerum Natura" (96-55 B.C.) by Lucretius in which he recognized the existence of "seeds" of disease as well as the "atomistic" nature of matter. It was not until the 1600's, when Antony van Leeuwenhoek developed a microscope with sufficient magnification, that these seeds became known as microorganisms. In the 18th century, the role of indirect transmission of disease was recognized. It was asserted that obstetricians spread puerperal sepsis, a frequent cause of maternal death, by wiping their dirty hands on lab coats while moving from patient to patient. Similar cases have led to reports centering on the role of clothing, linens, blankets, and other textiles in the dissemination of microbial infections (1-7). Sterilized textiles, on the other hand, may serve as a barrier to microorganisms, thereby reducing infection and the transmission of disease.

Microorganisms which cause infection in man generally are mesophilic for the temperature range of this class of organisms is similar to the temperature range of the human body. Bacteria can be classified according to the temperature where growth occurs: psychropiles growth range is 15 to 30°C, mesophiles 30 to 45°C, and thermophiles 55 to 75°C. A study by Church (8) reported that the following types of bacteria were commonly found in hospital bedding: Staphylococcus aureus, Staphylococcus albus, Streptococcus salivarius, Streptococcus thermophilus, Escherichia

coli, Sarcina lutea, Proteus vulgaris, Bacillus mycoides, and Bacillus subtilis. Hospital bedding may serve as a reservior for microbes pathogenic to man and as a means of contaminating other objects. Reports have shown, for example, that under certain conditions microorganisms from bedding have resulted in secondary streptococcal and staphylococcal infections (8). In addition, microorganisms can be transferred from the bedding to other areas during linen changes. Shaking the linen may allow the bacteria to become air borne and to settle on other objects, such as clothing and clean bedding, or to be trapped in nasal passages wherein they can be carried to other areas before being exhaled (8).

Because microorganisms can cause infection or disease and textiles can serve as carriers, it is necessary to utilize a reliable and efficient means of sanitizing textiles and textile products for health, sanitary, toiletry, and baby care products. The major methods of sterilization used today are: autoclaving and/or treatment with ethylene oxide gas which are applicable to hospital textiles, and ionization radiation which is used for industrial purposes. Another possible method of reducing microorganism populations on textiles is by exposure to microwave radiation (21, 35, 36). This method has been found useful in reducing bacteria populations in food, cosmetics, spices, and soil, but minimal research is available which explores the feasibility of using microwaves for sanitizing textiles.

Microwaves have been used in the textile industry to a limited extent for dyeing, drying, and finishing because it is a more efficient and uniform heating source than conventional heating methods. In addition, microwave equipment is more compact and the energy savings potential is greater (9-11). In order for a heating method to have industrial potential in the textile industry or for sanitization purposes, it must be safe,

effective, efficient, commercially feasible, and, at the same time, should not have detrimental effects on fiber properties. Needles, et al., (12) and Lyons (13) explored the effects of microwave exposure on textiles and found it slightly increased the tensile strength and elongation to break of cotton and polyester; whereas, wool and nylon fabrics showed a loss in strength with wool developing a loss in elongation and nylon obtaining an increase in elongation to break. They postulated that these changes in fiber properties were attributed to changes in molecular structure, as evidenced by the changes in dye absorption. Deeper shades were obtained on reactive-dyed cotton and disperse-dyed polyester after microwave exposure. Microwave treated nylon dyed a deeper shade with both disperse and reactive dyes. The dyeability of wool was changed slightly. Acid-dyed wool obtained a lighter shade; whereas, reactive-dyed wool dyed a deeper shade. Needles, et al., (12) also noted the melting points of nylon and polyester increased after microwave exposure.

Microwave radiation has been used in areas other than textiles for sanitization and sterilization (21, 35, 36). Because microwave energy is an efficient and uniform means of heating, it shows promise as a viable method for sterilizing textiles. The purpose of this study was to determine if microwave radiation can be used as an effective means of sterilizing textiles and to assess the sterilization efficiency of microwave energy on cotton and polyester fabrics. The effects of the microwave energy on the physical properties of fabrics also were evaluated in hopes that a working method of sanitization with minimal fabric degradation can be developed.

REVIEW OF LITERATURE

Nature of Microwaves

Microwave energy is high frequency radiation of 1 m to 1 cm wavelengths. This type of energy is expressed as millions of cycles/second or mega Hertz (MHz) with frequencies ranging between 300 to 30,000 MHz. The Federal Communications Commission has designated microwave frequencies of 890-940, 2400-2500, and 17,850-18,000 MHz for microwave processing (14). All other frequencies have been reserved for radar and communications. The microwave frequencies receiving primary attention today are 915 MHz, used for high-power industrial heating equipment, and 2450 MHz, used for domestic microwave ovens (15, 16). The main difference between equipment using these frequencies is the power output of the magnetron tubes: 915 MHz tubes are capable of producing an output of approximately 25 kW, whereas, 2450 MHz tubes are restricted to a much lower output of approximately 2.5 kW (16, 17).

The majority of microwave applicators (i.e., ovens, industrial equipment, etc.) produced today use a 2450 MHz frequency. The major microwave distributors in the United States no longer produce applicators using the 915 MHz frequency due to a low market demand. The major manufacturer of microwave applicators using 900-915 MHz appears to be Magnetronics Ltd., Leicester, England.

The penetration power of microwave radiation is inversely proportional to it's frequency. Mathematically, however, the absorbed energy increases as the frequency increases because the power capacity of a system is directly related to the frequency of the radiation and the

material's dielectric loss (15, 17). Industrial applications of microwave energy suitable for processing large quantities of materials require 915 MHz radiation because they have the penetrating power necessary for uniform heating. Domestic microwave ovens operate most efficiently at 2450 MHz for the quantity of materials usually is small and the greater penetration capabilities are not needed (15).

Microwave Heating Mechanism

The major uses of microwave energy are radar, communications, and heating. Most methods of temperature elevation apply heat to the surface of the substrate from a hot surface by radiation, conduction, or convection, such as hot plates, conventional dryers, or infrared heaters. Heating by these conventional methods is slow for the energy must be transferred numerous times before a material is heated to a uniform state. Microwave energy uniformly generates heat within a substrate and produces a rapid and direct transfer of energy or heat (16, 17).

Materials and water which can be heated by microwaves are termed "lossy". These materials have molecular structures with resonant frequencies similar to that of microwave radiation. When the frequencies are similar, a strong interaction occurs which causes the molecules to oscillate synchronously, thereby generating heat through intermolecular friction (13, 15-21). A frequency of 2450 MHz, for example, will cause the molecules to oscillate back and forth 2450 million times per second, causing friction and heat generation.

The amount of microwave absorption or heat generation depends upon the "lossiness" of a material. The amount of "lossiness" varies with the radiation frequency, temperature, and type of material being heated (15). Because water is "lossy", the presence of moisture in a

material will act as the heating mechanism.

Dry textiles do not appear to absorb microwaves to any great extent, therefore, moisture must be present for a temperature elevation to occur. Polyproplene and glass materials which have inherently low moisture regains are described as dielectric and absorb microwaves to a limited extent (16). These materials are used as conveyer belts for carrying materials through microwave applicators or units (16). Other components such as proteins, carbohydrates, and fats, if present in the exposed material, can increase the degree of "lossiness". The "lossy" components generate heat through molecular oscillation which, in turn, heats the textile substrate from the interior as well as the surface (19). Thus, if the absorbing components are evenly distributed, an extremely uniform heating will occur (16).

Microwave heating can be regarded as a form of dielectric heating (frequencies below 80 MHz) for both cause rapid reversal of a molecules polarity in an electrical field which developes heat (16, 19). There are distinct differences, however, between microwave heating and dielectric heating. Dielectric heating employs a low frequency and as high as possible field strength without electrical breakdown which would cause damage to the substrate by sparking or flash-overs (19). Microwave heating uses a low field strength and much higher radiation frequencies.

Efficiency and Cost

Microwave energy is extremely efficient for heating textiles. The energy is directed to the "lossy" component, such as the moisture within, and very little is expended in heating the textile (11). An energy utilization efficiency of more than 70% has been claimed for heating textiles by 915 MHz and 50 to 60% efficiency for 2450 MHz microwaves.

(This efficiency is based upon the conversion of electrical energy to heat energy in the treated material.) Microwave processing should become increasingly important as energy costs continue to rise.

Microwave Regulations and Applications

After the second world war, improved technology in radar and communications was developed through the use of microwave energy. Magnetron valves or microwave generators were developed from 1939 to 1945. Percy L. Spencer applied the knowledge of radar microwaves to heating and developed the principles of microwave heating. His work led to the evolution of the first domestic microwave ovens in the 1940's (18, 22). Industrial microwave units and the first affordable domestic microwave ovens were available to the general public in the mid 1960's (17). By 1970 it was estimated that 150,000 microwave ovens were in use in the United States (23).

The first type of microwave unit developed was the batch-type or domestic microwave oven, which operated at the 2450 MHz frequency with radiation being emitted from a power tube or magnetron in the oven cavity. Other developments in microwave units have centered on the industrial or belt-type units which differ from conventional ovens in the design of the microwave generating mechanism. Some of these developments have been: 1) five 1-2 kW parabolic radiators, 2) five 2 kW-power module units operating at 2450 MHz, 3) a continuous type microwave oven with one large power tube (25 kW) feeding microwaves into a tunnel through slits, 4) the meander system, used for drying textiles and paper, which emits energy at one end of the system only, and 5) the amplitron tube which produced 425 kW of 3000 MHz frequency (15).

Because large amounts of microwave energy leakage can be harmful,

energy trapping devices have been developed to prevent excess radiation leakage out of the ends of the tunnels or cavities of the units. Trapping devices serve a two fold purpose by preventing excess leakage and by absorbing energy when the tunnel is empty, thereby preventing the radiation from returning to the power tube which would cause damage (15). In a continuous microwave process in which materials are continuously moving in and out of the chamber, a trapping device is necessary as well as control of the size of the entrance and exit. Continuous processes utilizing 915 MHz microwave energy can allow larger openings than 2450 MHz with less potential of microwave leakage due to the lower penetrating power (15).

With the advent of microwave applicators for domestic and commercial uses, Federal Regulations for controlling microwave leakage have been developed. Before October 6, 1971, the maximum allowable leakage for domestic microwave ovens had been 10 milliwatts/cm (mW/cm) over any 0.1 hour. After this date the maximum allowable leakage was reduced to 1 mW/cm, as measured at 5 cm from any surface at the time of sale. An allowance of 5 mW/cm was established for the life of the applicator due to wear (24). Microwave ovens also are required to have a minimum of two operative safety locks, with one lock inoperable by humans to ensure the oven will not operate while the door is open (24). Manufacturers of microwave ovens are responsible for providing radiation safety and service instructions to distributors and warning labels indicating precautions for safe use (24).

Numerous reports have been made concerning the effects of microwave energy on animals and humans with the majority of the data pointing to local or general hyperthermia (over heating) as the result of exposure (25). However, there are still large areas of confusion, uncertainty,

and misinformation concerning the actual effects of microwave exposure on humans. It generally is accepted that microwave exposure causes overheating in specific areas of the body where relatively little blood circulates. Organs which do not possess an adequate vascular system for the exchange of heat, such as the testes and lens of the eye , are susceptible to thermal damage. These thermal effects have been documented, but the various reports on non-thermal effects are questionable. The best solution to warding off the effects of microwave exposure to humans is to stay within the 10 mW/cm exposure standard per 0.1 hour as set by the American National Standards Institute's (ANSI) C95.1 Standard (25).

Methods of Sterilization and Effect on Microorganisms

Because microorganisms can be contacted by the body through an open wound and by inhalation, it often is necessary to maintain sterile conditions in operating and hospital rooms to reduce the possibilities of contamination or infection. Studies have shown that dry textiles may serve as barriers to microorganisms; thus, fabrics are used as surgical gowns, caps, mask, and drapes, as well as for dressings to cover wounds (26, 27). Because textiles are used in areas where it is imperative to eliminate bacteria, efficient and reliable methods of sterilization before and after use or wearing must be practiced in hospitals and in other situations to prevent bacterial infections and disease.

The methods of textile sterilization available today are: moist heat or autoclaving, dry heat, ethylene oxide gas, and radiation sterilization. Of these, the major method of sterilization used in the medical field is autoclaving. In autoclaving, steam must come into intimate contact with the objects being sterilized to effectively kill all viable organisms. The lethality of moist heat upon microorganisms is attributed

to protein denaturation and coagulation, although the melting of membrane lipids also may be significant (28, 29). Proteins are readily denatured at lower temperatures if moisture or steam is present because the hydrogen bonds, which partially stablizes the configuration, are more readily broken if they can be bonded to water molecules (29). Microorganisms require higher temperatures in the dry state for irreversible damage to occur.

The four stages in autoclave sterilization are:

1) The air is removed from the chamber by a vacuum.
2) The steam pressure and temperature are increased to 15 psi, 121°C and held for 15 to 20 minutes.
3) The steam from the chamber is removed by post vacuuming which partially dries the objects.
4) The filtered air is admitted to cool and reduce the pressure.

For this method to be effective, 15 psi and 121°C must be obtained for 15 to 20 minutes (28). The time factor involved for the complete cycle depends upon the nature and amount of articles to be sterilized with the average time being 30 to 50 minutes. Textile objects are not dried completely in the autoclave chamber; thus, they must be wrapped and allowed to dry in a sterile area for an undetermined time. Sterile conditions during the final drying is extremely important because microorganisms are immediately carried throughout a wet textile due to capillary action (26).

Dry heat penetrates porous materials at a much slower rate than steam and requires more time and a higher temperature for the sterilizing action to take place; as a result, dry heat sterilization is less effective than moist heat autoclaving. The required conditions for this method to be effective are 165°C for one to two hours (28). Dry heat dehydrates and chars microorganisms, thus disrupting the cell and rendering them nonviable. Before textiles are sterilized by dry heat, they are washed,

dried, and packaged in metal containers (30). Packaging in containers eliminates recontamination of the textiles before usage. In addition to being less effective than autoclaving, dry heat treatments may degrade the fabric and/or finish; therefore, it's use is restricted.

The bulk of medical disposable products are sterilized by ethylene oxide gas (29). Ethylene oxide is an alkylating agent which replaces the unstable hydrogen atoms on $-NH_2$ and -OH present in proteins and nucleic acids, as well as -COOH and -SH groups of proteins found in microorganisms (29). This hydrogen atom replacement results in irreversible damage to vegetative cells and spores. Ethylene oxide is effective against both types of bacterial cells because it's small uncharged molecules can easily penetrate the cells (29).

The major advantage of ethylene oxide is that heat liable materials can be sterilized, but the method of application is extremely complex, requiring a thorough knowledge of application parameters (31). The main problem with ethylene oxide sterilization is assuring uniform diffusement of gas throughout the load. In addition, the sterilizing action is slower than with steam sterilization. Other factors which restrict the usage of the ethylene oxide method are the rising cost of the gas which is a crude oil derivative, possible residual toxicity, and a proposed ruling from the Enviromental Protection Agency stating that the gas is a mutagen and/or carcinogen (32).

A method of non-heat sterilization comparable with ethylene oxide is radiation with electron beams generated by high power, particle accelerators or by gamma radiation produced by cobalt 60 or cesium 137 (32, 33). Due to the initial expense, cobalt 60 facilities are very limited, whereas electron beam processing is readily available (32). Radiation inactivates microorganisms by causing ionization in the cell,

resulting in alterations in protein bases, and single and double stranded breaks in the DNA (29).

Radiation can be used to sterilize disposable textile materials which are used once and then disposed, but textiles generally are degraded by high energy radiation. Cotton irradiated with large doses of gamma radiation results in carbonyl and carboxyl group formation, chain cleavage, increased solubility in water and dilute alkale, and a decrease in tensile strength (33).

Radiation doses of one megarad or 10^{-5} joules are sufficient to sterilize both cotton yarn and fabric. At low doses of radiation, the tensile strength of cotton increases before it decreases. Thus, if doses are kept low, reusable textiles may with stand this type of sterilization (33). The main advantages of radiation sterilization are:

1) The materials can be prepackaged in thermoplastics and foils.
2) The process is cold which allows heat sensitive materials to be sterilized.
3) The quantity of materials sterilized may be large.
4) After the initial investment, the cost is less than with ethylene oxide because large volumes of materials can be accomodated at one time (32, 34).

Another interesting method of reducing microorganism populations which has not been used on a large scale, is the use of microwave radiation. Microwave radiation has been found useful in sanitizing cosmetic color additives, food, spices, and soil (21, 35, 36). Combining microwave radiation with an inert coolant gas under superatmospheric pressure will sterilize heat liable food and biological materials such as whole blood and plasma (14). Another method of sterilization employs microwave energy and steam under pressure for metallic and nonmetallic

materials such as surgical instruments and dressings (37). Employing infrared radiation and microwave energy in a superatmospheric steam environment also will create a sterilizing effect (14). Minimal research is available, however, which explores the feasibility of using microwaves for sterilizing textiles.

Microwave energy is being employed extensively to heat foods rapidly both commercially and domestically. Several research studies have examined the effects of microwave heating on microorganisms in foods. Some of the significant conclusions reached through these studies are:

1) The presence of water and other "lossy" materials increases the efficiency of microwaves in reducing bacterial counts as well as reducing the amount of moisture present (21).

2) The destructive potential of 915 MHz microwaves is consistently higher than 2450 MHz and conventional heating methods (38).

3) The natural bacterial content of foods often is reduced to a greater extent than laboratory inoculated foods (38).

4) Vegetative type cells are completely eliminated in microwave cooked food, and sporeforming cells are greatly reduced (38, 39, 40).

5) Bacterial spores are not eliminated completely in microwave exposures, but it is more lethal than equivalent conventional heating (40, 41).

6) Bacterial classification has an effect on the microwave lethality. Gram negative and mesophilic bacteria are reduced 97-99%; whereas Gram positive and thermophiles are more tolerant (18, 21, 38).

7) The temperature required to destroy microorganisms is often 10°C below the normal thermal death point or close to the optimum growth temperatures (21).

8) The amount of organism reduction does not always reach 100% (39, 42).

9) The chemical composition of microorganisms (high concentrations of ionizable compounds) may allow the cells to be selectively heated, thus reaching higher temperatures than the surrounding medium (23, 43).

10) The various types of Gram negative bacteria require approximately the same exposure levels to be eliminated.

Much controversy exists as to the exact nature of microorganism destruction by microwaves. Numerous studies, for example, have reported that non-thermal effects are responsible for rendering microorganisms non-viable (21). Other researchers support the premise that the destruction of organisms irradiated with microwaves is attributed to thermal inactivation (21). One reason for this difference in opinion is the varying procedures and microwave frequencies used for evaluation. The general concensus is that the main destructive effects of microwave energy are thermal in nature, but non-thermal factors also come into play since the temperature of microorganism inactivation is generally lower than conventional heat inactivation (21).

The mechanisms involved in thermal inactivation of microorganisms during microwave exposure is thought to be similar to those associated with moist heat sterilization in which the hydrogen bonds of the proteins are broken and reformed with water molecules, resulting in protein denaturation and coaggulation (29). Because opinions differ concerning the non-thermal effects of microwaves, the exact nature of this type of destruction is not known.

Olsen et al. (21) reported that bacterial spores treated in a microwave field germinated on an "all-or-nothing" basis, unlike conventional thermal treatment. This may indicate that microwaves are affecting a metabolic system other than that affected by thermal energy. Microwaves also caused resonant action or structural reversals of the cell's components, resulting in chromosome aberrations due to alignment in the field, morphological changes in cell nuclei, and changes in electrophoretic peaks of certain proteins (21). These types of changes arrived at non-thermally also may cause cell death.

Bacterial cells form a pearl chain formation or unidirectional

orientation after several minutes in the microwave field (21). This type of orientation usually does not have a destructive effect on microorganisms, for thermal destruction will occur first. Microwave exposure also reduces: the transport of Na^+ across a membrane, selective permeability, conductivity (such as an increase in ionic strength), and the zeta potential which allows bacterial clumps to form, making a better target for the radiation (21).

Significance of Study and Objectives

A sanitization method employing microwave energy of 2450 MHz would find merit in the medical field as a rapid and efficient method of sanitizing surgical gowns, theatre drapes, masks, caps, and contaminated bed linens, as well as in industry for sterilizing sanitary products such as bandaids, diapers, baby clothes, femine products, and artificial organs and arteries. Microwave heating methods currently are being developed in the textile industry for drying and dyeing fabrics. Coupling the drying and sanitizing processes in hospital laundries could result in the development of an extremely efficient and energy saving, one-step-method for drying and sanitizing textiles. Such a system could reduce energy consumption for drying and sanitizing, as well as cut capital expenditures in hospitals by utilizing one piece of energy efficient equipment for both drying and sterilizing.

Sanitization methods must be effective without causing excessive fiber or fabric degradation. Thus, this study also assessed the effects of microwave radiation on the physical properties of cotton and polyester fabrics.

The objectives of this study were:

1) To assess the degree of textile sanitization obtainable with microwave energy of the 2450 MHz region.

2) To determine if the sanitization potential of microwaves is influenced by the moisture content of textiles and if the process is applicable to both hydrophobic and hydrophilic fibers.

3) To elucidate optimum exposure times and radiation intensities necessary to achieve minimum acceptable levels of sterilization on textiles.

4) To evaluate the effects of microwave energy on the physical properties of cotton and polyester fabrics by means of tensile strength and elongation.

5) To determine the amount of moisture reduction due to the drying effect of microwave radiation on textiles.

PLAN OF PROCEDURE

The purpose of this study was to determine the effectiveness of 2450 MHz microwave energy in sanitizing selected textiles: a hydrophilic fabric (cotton), and a hydrophobic fabric (polyester). Fabrics were inoculated with a known number of organisms, irradiated with 2450 MHz microwave energy, and then evaluated in terms of the percentage of non-viable organisms present after microwave exposure. Also investigated in this study were the effects of microwave radiation on the tensile strength elongation, and moisture content of the cotton and polyester fabrics after 0, 1, 3, 5, and 7 minutes of microwave exposure.

Experimental Fabrics

The following fabrics for this study were obtained from Testfabrics, Inc.:

1) Bleached and mercerized, 100% cotton, print cloth, plain weave with 94 x 80 thread count (style #400M)
2) 100% spun Dacron 54, polyester, plain weave with 64 x 57 thread count (style #767)

The fabrics were washed prior to testing in AATCC Detergent 124 using washing and drying procedures IIB in AATCC Test Method 123-1978 (44). The pre-wash adjusted variations in pH and removed any processing residues which may have inhibited bacterial growth.

Samples of cotton and polyester fabrics, measuring 5 x 5 cm, were wrapped in brown paper, and sterilized by autoclaving at 121°C and 15 psi for 20 minutes. After removal from the autoclave chamber, the samples remained wrapped until needed for testing to maintain their sterile condition.

Microorganisms

Cultures of Staphylococcus aureus, strain 209, ATCC (American Type Culture Collection) No. 6538; Escherichia coli, Crookes strain, ATCC No. e8739; and Bacillus cereus spores were obtained from Grain Science Marketing Department, Kansas State University. These organisms were selected for this study because 1) they represent three of the main types of bacteria found in the hospital environment and 2) they represent the three main classes of bacteria: Gram positive, Gram negative, and spore former (8). Cultures of each organism were prepared which contained approximately 7×10^5 organisms/ml based on a turbidity-viable count standard. The specific number of organisms/ml was determined immediately before microwave exposure by removal from an inoculated, unexposed fabric sample.

Culture Media

Media suggested by ATCC were used for cultivating all organisms. Staphylococcus aureus was cultivated on a micrococcus media consisting of 5 g of peptone, 3 g of yeast extract, 1.5 g of beef extract, 1 g of glucose, 15 g agar, and 1 liter of distilled water. Difco Nutrient agar (Difco No. 0001) was prepared for cultivating Escherichia coli and Bacillus cereus by dissolving 23 g of the agar in 1 liter of distilled water.

Microwave Unit

A Sharp Carousel microwave oven, Model No. R-6770, operating at 2450 MHz with a 650 W output, was used to irradiate the fabric samples. The unit was equipped with an inner turntable which allows a more even heat distribution than other microwave ovens that require rotation of materials 180° halfway through the exposure period.

Temperature Measurement

Tempilabels (Omega Engineering, Inc., Stamford, Conn.) were used to determine the maximum temperature obtained during sample exposure to microwaves. The labels consisted of four temperature sensitive dots in 5 to 6 degree increments. Four sets of labels were used ranging from 60 to 127°C. Preliminary tests were made with a digital thermometer to compare the temperature monitoring accuracy of the labels.

Comparison of Test Methods for Evaluating the Population of Microorganisms

Prior to the microwave testing, a suitable method for determining the number of viable organisms on a fabric was determined by comparing two existing test methods. The methods evaluated were 1) a direct count procedure (Quinn Test) in which the organism counts were made directly on the fabric and 2) a bacterial removal procedure in which colony counts were made after the bacteria had been removed from the fabric. The second procedure was obtained from AATCC Test Method 100-1974, Evaulation of Antibacterial Finishes on Fabrics (44).

Sample Preparation

For the Bacterial Removal procedure (Modification of AATCC Test Method 100-1974), fabrics were inoculated by immersing three 5 x 5 cm samples of each fabric in 10 ml of culture containing approximately 7×10^4 organisms/ml. The culture and samples were shaken to thoroughly wet-out the fabrics and distribute the bacteria. To enumerate the actual number of cells/ml, one-tenth ml of the culture was placed in a 9.9 ml dilution tube and gently tapped to distribute the bacteria.

For the Quinn Test (Direct Count Procedure), three 5 x 5 cm samples of each fabric were placed in a solution containing approximately 7×10^4 organisms/ml and shaken. After inoculation, the test samples

were placed in a desiccator to dry for 24 hours.

Quinn Test (Direct Count Procedure). This is a qualitative test for assessing bacterial growth on fabrics. In this study, it was used to determine if a direct population count on the fabric samples was feasible. The inoculated and desiccated fabrics were placed in a sterile agar plate and covered with a thin layer of agar. After incubating for 24 to 48 hours, the number of colonies on the fabric samples were counted under low power magnification.

Bacterial Removal Procedure (Modification of AATCC Test Method 100-1974). This test method originally was developed to determine the antibacterial properties of fabric finishes. The basis of this test method is inoculating fabric samples with bacteria, and then removing the bacteria for population counts. This method was used to meet the requirements of this study.

Each inoculated and desiccated fabric was placed in 100 ml of a 0.0125% peptone solution and shaken vigorously for one minute to remove the organisms from the fabric. After removal, 0.1 ml of the solution was spread on a sterile agar plate and incubated for 24 to 48 hours, and then the number of colony-forming units were counted and multiplied by the number of dilutions to obtain the total number of organisms/ml.

The method obtaining the highest and most reliable bacterial count with the greatest efficiency was used in determining the number of viable organisms per fabric sample before and after exposure to microwave radiation.

Inoculation of Fabrics and Microwave Exposure

The main purpose of this study was to determine if microwaves of the 2450 MHz region would sanitize textiles to a degree similar to autoclave sanitization. Fabric samples were inoculated with organisms and exposed to microwave energy for 0, 1, 3, 5, and 7 minutes in a steam contained and steam released environment. In order to compare microwave sterilization with conventional autoclave steriliation, additional samples were autoclaved for 20 minutes at 15 psi and 121°C. After exposure the number of remaining viable organisms was determined.

Fabric Preparation

Six dry, sterilized samples of each fabric were inoculated by placing them in 300 ml sterilized jars containing 40 ml of culture and at least 7×10^4 organisms/ml. The flask was shaken to wet-out the fabrics and distribute the bacteria. It was assumed the bacteria was evenly distributed on the samples since a wet fabric allows easy passage of bacteria throughout the sample (27). The wetted-out samples were placed between two layers of blotting paper which had been sterilized in a drying oven for two hours at 165°C. Pressure was applied to the blotting paper containing the samples for 10 seconds to reduce the samples moisture content which simulated the amount of moisture present after the last spin cycle of an automatic washing machine. The high moisture content was considered important because this study was investigating the feasibility of simultaneous microwave sterilization and drying.

One of each of the inoculated, blotted samples was used as a control to determine the initial number of organisms and to assure the preparation method did not render the organisms non-viable. One sample of each fabric was autoclaved for 20 minutes at 15 psi and 121°C in order

to compare microwave sterilization with an established sterilization method. The remaining five samples of each fabric type were placed in sterile covered dishes and exposed to microwave radiation for 1, 3, 5, and 7 minutes. The covered dishes served as a steam containing mechanism which ideally would enhance the amount of death due to greater steam penetration. The procedure was repeated with the lids of the petri dishes removed, which permitted the steam to be released as it evolved and simulated a one-step drying and sterilizing process.

During microwave exposure, a Tempilable of appropriate temperature range was placed beneath the sample to record the maximum temperature attained. After each exposure time, the percent organism reduction was determined by the method found most reliable in the initial testing.

Two replications of the above procedure was carried out for each of the three bacteria types. Additional steps were necessary to obtain meaningful results from the Bacillus cereus strain. Since Bacillus cereus is a sporeformer and spores were present, it was necessary to induce germination after microwave exposure to determine if the spores were non-viable or merely remained in a dormat state. A portion of the solution used to remove the bacteria from the fabric after exposure was heated at 80°C for 20 minutes. After heating, 0.1 ml of the solution was plated and incubated for 24 to 48 hours, and then the number of colonies were counted and compared to the number of colonies from the initial microwave treated solution. The difference in the colony counts indicated the number of dormant cells remaining after microwave exposure.

The total number of colony forming units remaining after microwave exposure were recorded and converted into percent organism reduction by the following equation:

$$\% \text{ Organisms Reduction} = \frac{A - B}{A}$$

A = number of colony forming units in the control sample
B = number of colony forming units after exposure

The maximum temperature attained during exposure also was recorded.

Determination of Moisture Content

Microwave energy has been found useful as a method of drying textiles. Changes in the moisture content of the microwave exposed samples were assessed to determine the feasibility of combining microwave sterilization and drying. The percentage change in the moisture content of the samples was determined by weighing the samples before and after microwave exposure according to ASTM D 2654-76, Moisture Content and Regain of Textiles (45).

Ten 5 x 5 cm samples of each fabric were wetted-out for 5 minutes in distilled water and placed between two layers of blotting paper which had been dried for two hours at 165°C in a drying oven. Pressure was applied to the blotting paper containing the samples for 10 seconds to reduce the samples moisture content which simulated the amount of moisture present after the last spin cycle of an automatic washing machine. The samples were weighed after removal from the blotting paper and exposed to microwaves in covered and uncovered petri dishes for 0, 1, 3, 5, and 7 minutes. After the exposed samples were cool, they were reweighed and placed in a drying oven for two hours and weighed each 15 minutes thereafter until three identical, consecutive weights were obtained. The percent moisture content was determined for each sample before and after exposure by the following equation:

$$\% \text{ Moisture Content} = \frac{A - B}{A}$$

A = wet weight or weight after microwave exposure
B = oven-dry weight or bone-dry weight

Tensile Strength and Elongation of Fabrics after Microwave Exposure

Needles, et al. (12) reported that microwave energy of the 2450 MHz region increased the strength of wet polyester and cotton warp yarns after one minute of exposure. Minimal information is available on the effects of increased microwave exposure levels on fabric strength and elongation. This portion of the study determined the effects of 1, 3, 5, and 7 minutes of microwave exposure on the tensile strength and elongation of wet and dry polyester and cotton fabrics.

ASTM Test Method D 1682-64, Breaking Load and Elongation of Textile Fabrics, Ravel Strip Method (45) was used to evaluate the effects of microwave exposure on tensile strength and elongation of the polyester and cotton fabrics. A Scott Tester, CRE (constant-rate-of-extension) tensile testing machine, with a three inch jaw seperation and two inch clamps, was used to perform the testing. Samples measuring 3.9 x 15.3 cm were cut from each fabric type in the warp direction and raveled to 2.54 x 15.3 cm. Three strips were randomly assigned to each exposure time of 0, 1, 3, 5, and 7 minutes for each condition of wet and dry. Wet fabric samples were prepared by wetting-out the samples in distilled water for 5 minutes and then spinning dry in an automatic washing machine. The samples were wrapped in a plastic wrap to maintain the moisture during microwave exposure. Dry samples were conditioned at $21 \pm 2^{\circ}C$ and 65% relative humidity before microwave exposure.

After microwave exposure, the samples were reconditioned and tested for changes in strength and elongation. Breaking strength was recorded

in kilograms and elongation at break was expressed as percentage elongation based on the initial gauge length.

Statistical Analysis

The data percentages for each test was analyzed for significance using an analysis of variance procedure. The area of significance for variables of exposure time, fabric type, and condition was determined with Duncan's Multiple Range Test for Variance. The statistical testing was performed by the Kansas State University Statistics Department using a three factorial design from statical package SCL04675.

Hypotheses

1) There will be no significant difference in the bacterial populations between cotton and polyester fabrics exposed to microwave energy for 0, 1, 3, 5, and 7 minutes.

2) There will be no significant difference between the bacterial counts on fabrics exposed to microwave energy in the steam released state compared to those in the steam retained state.

3) There will be no significant difference in the bacterial counts among the three types of bacteria after microwave sanitization.

4) There will be no significant difference in the physical properties of the fabrics before and after microwave sanitisation.

RESULTS AND DISCUSSION

Evaluation of Population Counting Methods

AATCC Test Method 100-1974 (44) was superior to the Quinn Test when ease of population counting and procedure were compared. The Quinn Test is a qualitative method which resulted in unprecise results when attempts were made to count 7-900 organisms on a 5 x 5 cm fabric surface under low power magnification. Many of the colonies locked between the fabric yarns were difficult to view because of the similarities in color between the fabric and colonies. In addition, the thin agar layer prescribed in the Quinn Test was difficult to apply to the polyester samples because of it's hydrophobic nature. The agar rolled off the sides of the sample, forming a thicker layer beside the sample. This problem did not exist with the hydrophilic cotton samples, however. Application of the agar removed organisms from all the samples which formed colonies on the agar surface. The dense surface colonies complicated population counting on the fabric surface below. Organism growth on all the samples appeared to be inhibited by the agar layer due to the reduction in the amount of oxygen supplied to the obligate aerobic organisms.

The AATCC Test Method 100-1974 allowed more flexibility in the number of organisms used because serial dilutions facilated the reduction of the large number of organisms to a countable number (30-300/plate). A large number of organisms was necessary to ensure reliable and valid data. There did not appear to be any difficulties in shaking the bacteria off the samples into the water because the number of organisms removed

from three samples inoculated by the same culture gave similar colony counts (see Figure 1.).

The AATCC Test Method 100-1974 was used in determining population counts in the microwave exposure tests due to reproducability and ease of counting colony forming units. The sensitivity of this counting procedure was $\pm$ 10 organisms/ml. Therefore, a reference to 100% reduction is not accounting for the possibility of ten organisms remaining in the removal solution. This sensitivity was acceptable because 10 organisms remaining from 7×10^4 organisms is a 0.0144% error.

Effect of Microwave Exposure on Bacterial Reduction

Staphylococcus aureus

Microwave exposure time was found to be the only significant variable by an analysis of variance procedure for bacterial reduction (Table B1). In General, as the microwave exposure time increased, the percentage reduction in bacteria progressively increased (Figures 2 and 3). The Duncan's Multiple Range Test for Variance revealed a significant reduction between one and three minutes of exposure for Staphylococcus aureus (Table B2). There was no significant difference in the mean number of viable organisms on the unexposed fabric controls and the samples exposed to microwave radiation for one minute. The differences in the mean number of viable organisms on the samples exposed 3, 5, and 7 minutes also was not significant.

Escherichia coli

The percentage reduction of Escherichia coli was 100% after three minutes of microwave exposure. The significance of this reduction can not be proven statistically, for the usual statistical tests are not applicable due to the small amount of variance between all exposure

Organism	Number of Colony Forming Units					
	Polyester Samples			Cotton Samples		
	#1	#2	#3	#1	#2	#3
Staphylococcus aureus	2.13×10^5	2.09×10^5	1.90×10^5	2.92×10^5	3.10×10^5	2.86×10^5
Escherichia coli	2.68×10^5	2.73×10^5	2.59×10^5	2.11×10^5	1.94×10^5	1.86×10^5
Bacillus cereus	1.73×10^5	1.65×10^5	1.71×10^5	1.56×10^5	1.49×10^5	1.51×10^5

Figure 1. Comparison of Bacterial Counts Removed from Fabric Samples.

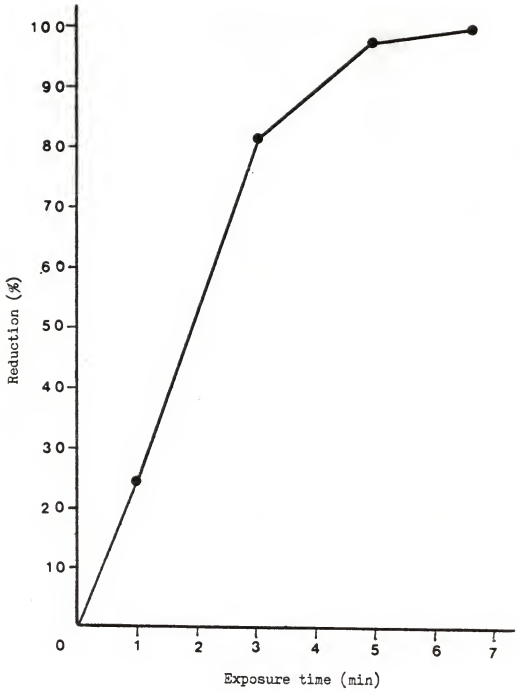

Figure 2. Effect of Microwave Exposure on Percentage Reduction of Staphylococcus aureus.

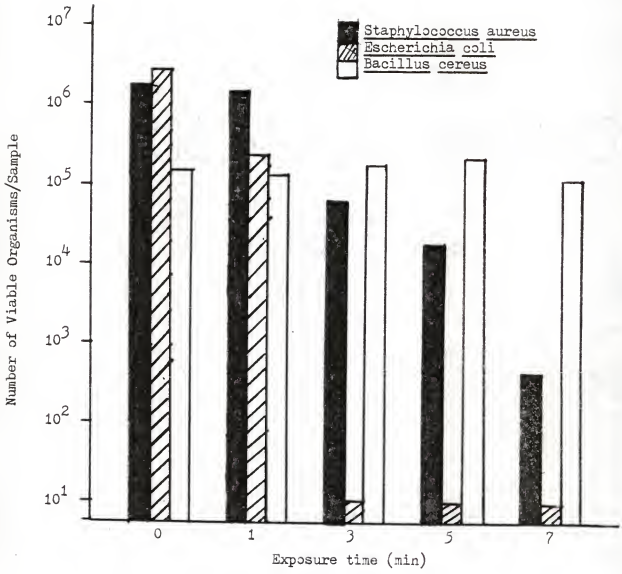

Figure 3. Mean Number of Viable Organisms after Microwave Exposure.

times. Figures 3 and 4 portray the actual and percentage reduction of Escherichia coli for samples exposed to microwave radiation for 0, 1, 3, 5, and 7 minutes.

Bacillus cereus

The analysis of variance procedure did not show a significant reduction of Bacillus cereus spores after 0, 1, 3, 5, and 7 minutes of microwave exposure (Table B3). The data analysis was performed on the percentage reduction of the total population counts obtained by combining the microwaved population counts and the heat-activated population counts for each sample (Tables A7 and A8). The microwave treated population counts yielded data on the number of viable cells in the inoculum and the number of spores which germinated after microwave exposure. The microwaved count increased slightly or stayed relatively constant for all exposure times. This indicates that microwave exposure destroyed some spores and/or caused some spores to germinate.

The total percentage reduction of Bacillus cereus was extremely sporadic. With some exposure times, the population was reduced and in other exposure times the population increased. Figure 5 shows the percentage reduction of Bacillus cereus after microwave exposure. This graph indicates that exposure periods over five minutes may have a lethal effect on spores.

Comparison of the Lethal Effects of Microwaves on Microorgansims

The percentage reduction of the three bacteria types occurred as expected. The Gram negative Escherichia coli was the most susceptive to microwave exposure for 100% reduction was obtained in three minutes. The Gram positive Staphylococcus aureus was more resistant than Escherichia coli, obtaining 100% reduction in seven minutes. The spore former,

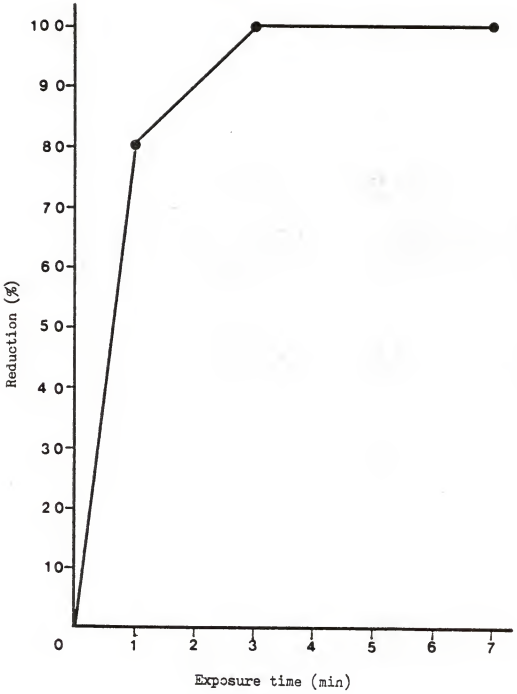

Figure 4. Effect of Microwave Exposure on Percentage Reduction of Escherichia coli.

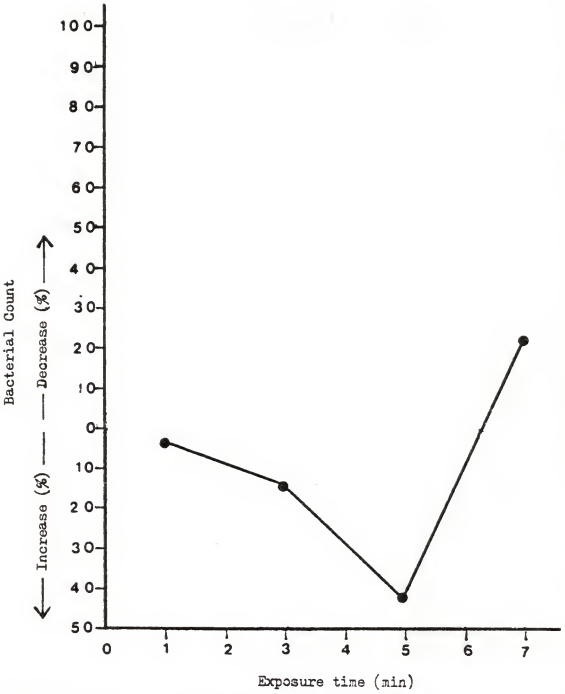

Figure 5. Effect of Microwave Exposure Time on Percentage of Bacillus cereus.

Bacillus cereus, was the most resistant bacteria type, for 100% was not approached after seven minutes of microwave exposure. These results coincide with information obtained from other studies which reported: Gram negative bacteria was reduced 97-99%; whereas, Gram positive bacteria are more tolerant, and spores are not completely eliminated in microwave exposures (18, 21, 38, 40, 41). The hypothesis that there will be no significant difference in the bacterial counts among the three types of bacteria after microwave sanitization was rejected.

Effect of Temperature on Bacterial Reduction

Tempilabels used to measure the maximum temperature attained during microwave exposure periods, consisted of dots of temperature sensitive materials which turned black when the respective temperature was attained. Since the dots were in 5-6° increments, only temperature estimates cound be realized. Difficulties also arose when the dots partially turned black and when a dot did not turn black but the next temperature increment dot did turn black. In these instances, the highest temperature dot with partial or total color change was recorded.

A linear relationship was observed between mean temperature and exposure level (Figure 6). Mean bacterial reduction of Staphylococcus aureus and Escherichia coli also increased with exposure time (Figure 7). This relationship indicates that the percentage reduction of vegetative cells is dependent upon the temperature attained during microwave exposure.

Effect of Fabric and Condition on Bacterial Reduction

The analysis of variance procedure showed that fabric type (i.e., polyester and cotton) and exposure conditions (i.e., steam released and steam contained) had no significant effect on bacterial population reduction during microwave exposure (Table B1 and B3). The mean

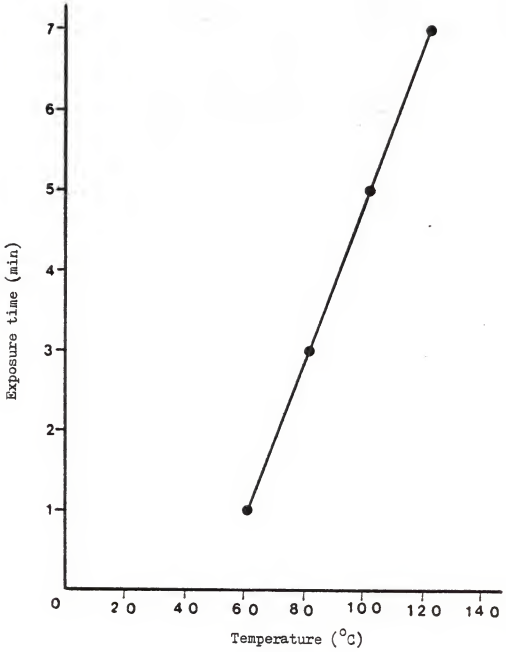

Figure 6. Mean Temperature Attained during Microwave Exposure.

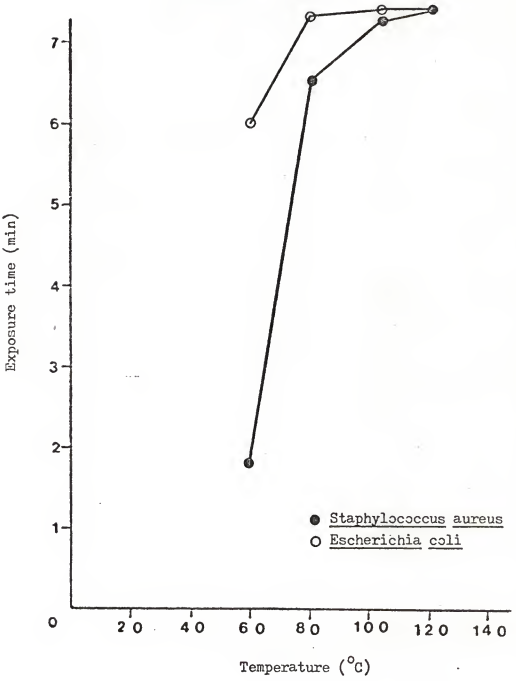

Figure 7. Effect of Microwaves Exposure Time on Temperature Attained in Fabrics Treated with Staphylococcus aureus and Escherichia coli.

percent bacterial reduction per exposure time was similar for polyester and cotton and almost identical for the conditions of released and contained steam (Figures 8 and 9). Therefore, the hypothesis that fabric type and condition will not have an effect on bacterial reduction was accepted.

The effect of microwave exposure times and temperature attained on the percentage reduction of Staphylococcus aureus, Escherichia coli, and Bacillus cereus for cotton and polyester exposed under steam released and steam contained conditions is shown in Figures 10 to 15. Although there were some differences associated with fabric type and condition, they were not significant.

Effect of Microwave Exposure on Strength

Mean tensile strength values are given in Table A9. Each mean was calculated from three measurements.

The analysis of variance procedure indicated that microwave exposure time, and fabric type had a significant effect on the tensile strength at the .01 significance level. The second order interactions of exposure time x condition and fabric type x condition also were significant (Table B4). A subsequent Duncan's Multiple Range Test for Variance showed tensile strength increased significantly between one and three minutes of microwave exposure (Figure 16 and Table B5). The strength of cotton and polyester fabrics also was significantly different (Tables B6 and B8). The steam released fabrics exposed to one and three minutes of microwave exposure was significantly stronger than other exposure times and conditions (Tables B7 and Figure 17). The mean percentage strength changes in polyester and cotton associated with specific microwaves exposure times and conditions are represented

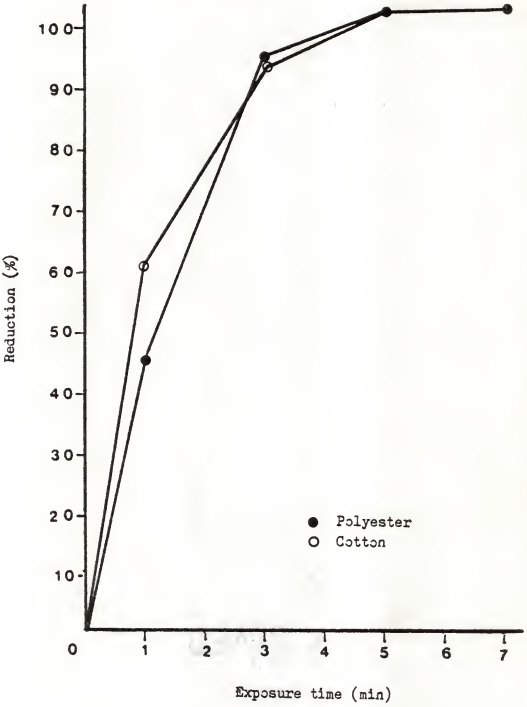

Figure 8. Effect of Microwave Exposure Time on Percent Reduction of Vegetative Cells on Polyester and Cotton Fabrics.

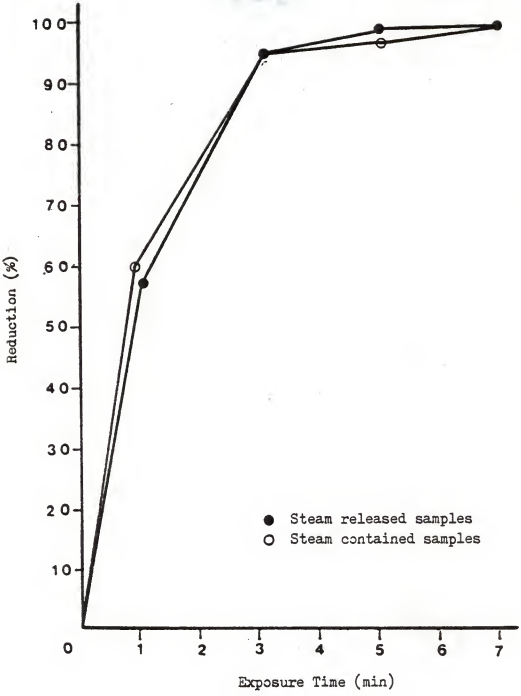

Figure 9. Effect of Microwave Exposure Time on Percentage Bacterial Reduction of Steam Released and Contained Samples

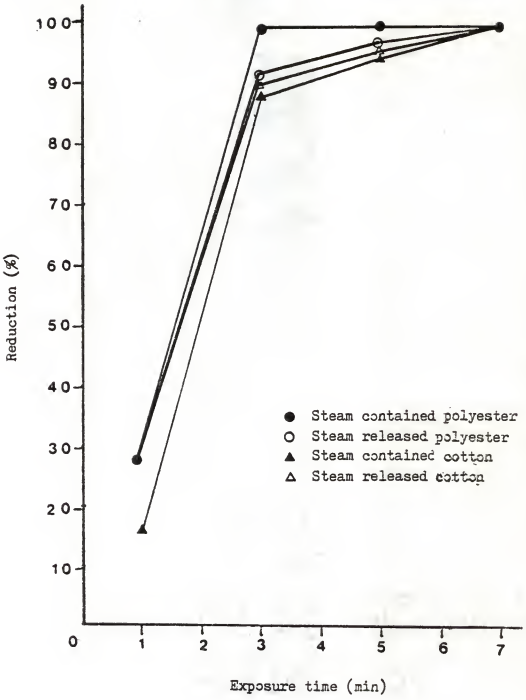

Figure 10. Effect of Microwave Exposure Time on the Percentage Reduction of Staphylococcus aureus for Steam Released and Steam Contained Cotton and Polyester Fabrics.

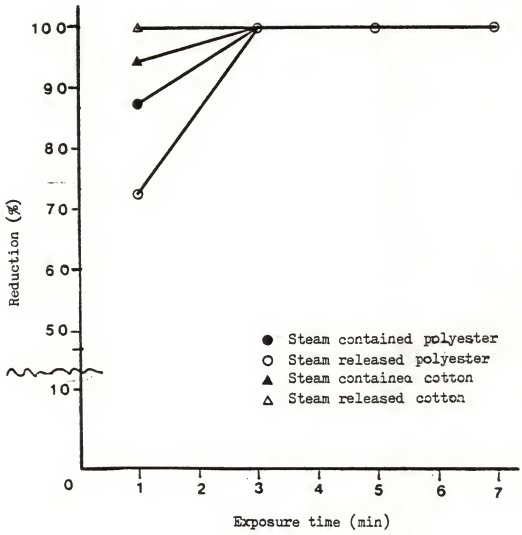

Figure 11. Efffect of Microwave Exposure Time on Percentage Reduction of Escherichia coli on Steam Released and Steam Contained Polyester and Cotton Fabrics.

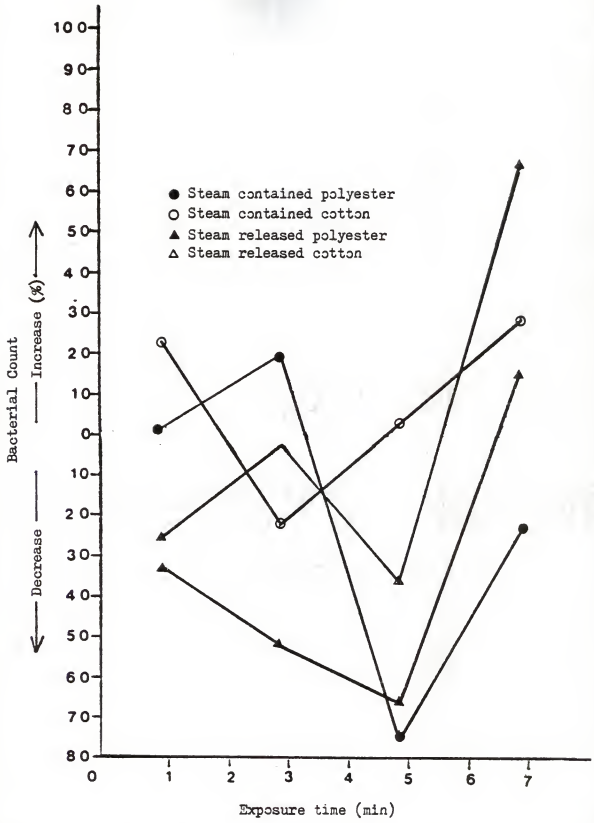

Figure 12. Effect of Microwave Exposure Time on Percentage of Bacillus cereus on Steam Released and Steam Contained Polyester and Cotton Fabrics.

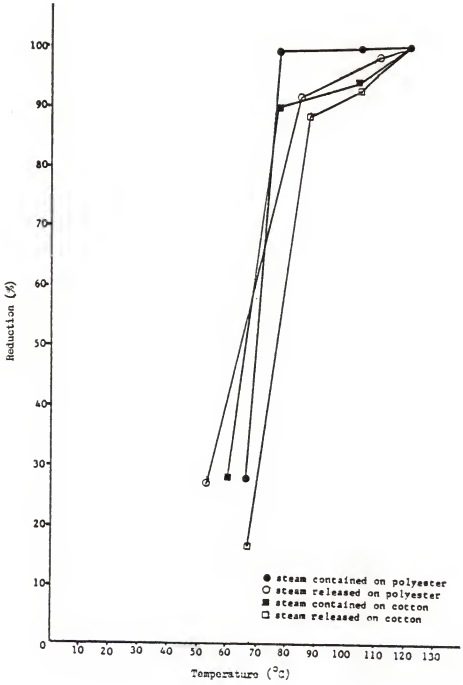

Figure 13. Effect of Temperature during Microwave Exposure on the Percentage Reduction of Staphylococcus aurous on Steam Released and Contained Polyester and Cotton Fabrics.

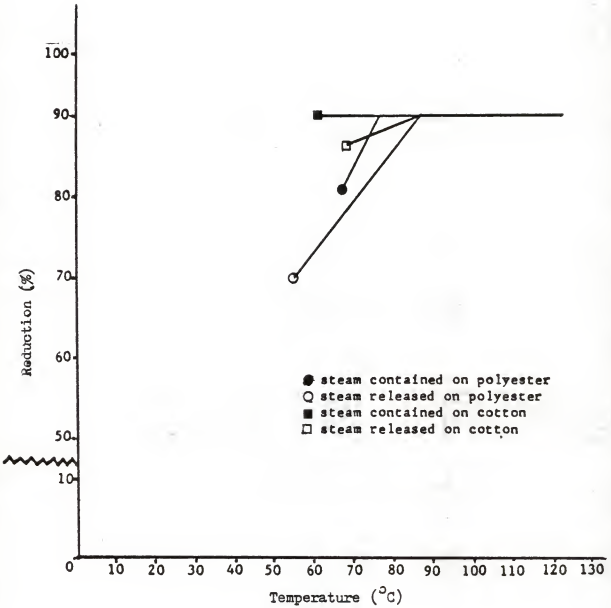

Figure 14. Effect of Temperature during Microwave Exposure on the Percentage Reduction of Escherichia coli on Steam Released and Steam Contained Polyester and Cotton.

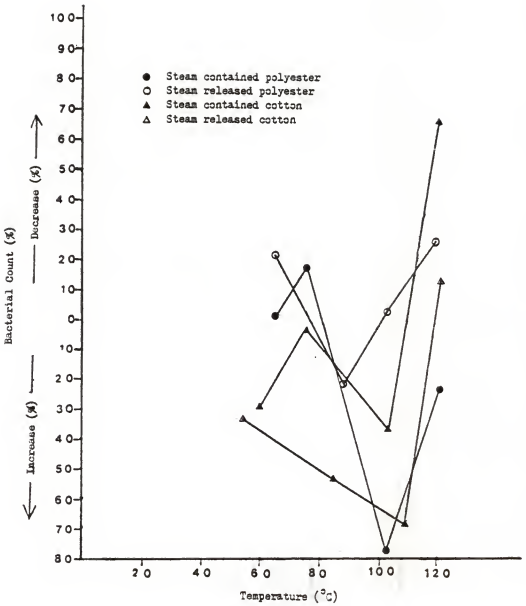

Figure 15. Effect of Temperature during Microwave Exposure on the Percentage of Bacillus cereus on Steam Released and Steam Contained Polyester and Cotton Fabrics.

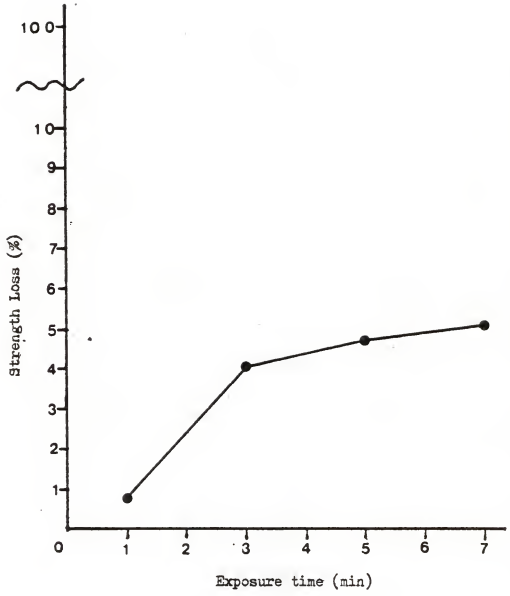

Figure 16. Effect of Microwave Exposure Time on Percentage Strength Loss.

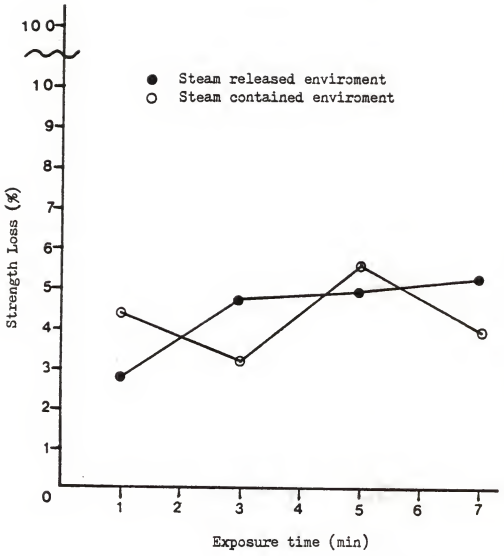

Figure 17. Effect of Microwave Exposure Time on the Percentage Strength Loss in Steam Contained and Steam Released Fabrics.

in Figure 18. The hypothesis that there will be no significant difference in the physical properties of the fabrics before and after microwave sanitization was rejected.

Effect of Microwave Exposure on Elongation

An analysis of variance procedure indicated that the independent variables of exposure time, fabric type, and condition, or interactions of these variables, had no significant effect on elongation. The mean percentage changes in elongation for each fabric type and condition are presented in Figure 19.

Moisture Content after Microwave Exposure

The analysis of variance procedure for percentage moisture reduction indicated that exposure time, and fabric type significantly influenced moisture content (Table B10). Duncan's Multiple Range Test for Variance showed a significant difference in moisture content existed after one and five minutes of microwave exposure (Table B11). A significant difference was also shown between the moisture contents of polyester and cotton fabrics, as expected (Table B12).

Microwave heating was more efficient in reducing the moisture content of the fabric samples than conventional drying ovens. Bone-dry conditions were obtained in fabric samples after $2\frac{1}{2}$-3 hours of convection oven heating; bone-dry weight was reached in seven minutes with steam released microwave heating. As was expected, the steam contained environment usually did not allow the samples to reach bone-dry state.

Cotton samples had a higher moisture regain than polyester due to it's hydrophilic nature. Cotton samples also lost a larger amount of moisture quicker than polyester, thus reaching the bone-dry state first in the steam released enviroment.

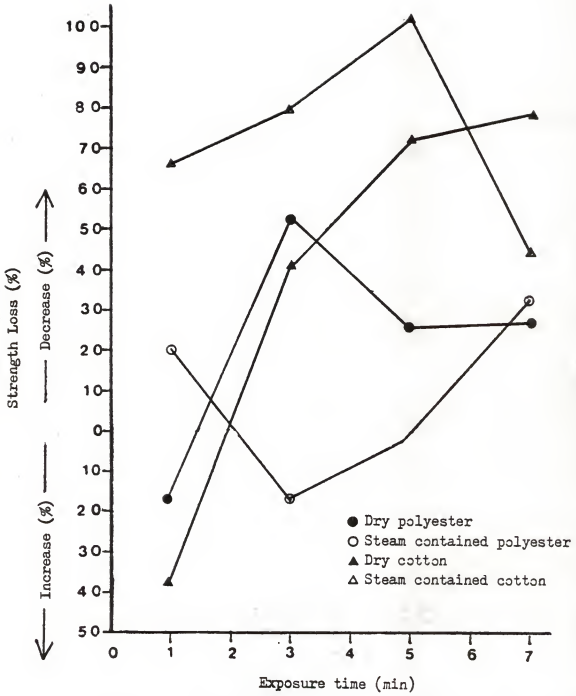

Figure 18. Effect of Exposure Time on the Percentage of Strength Loss of Steam Released and Steam contained Polyester and Cotton Fabrics.

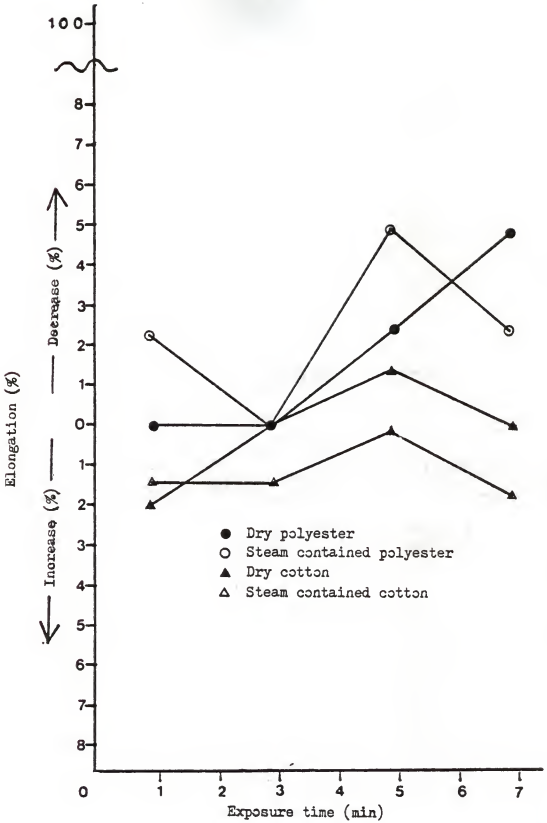

Figure 19. Effect of Exposure Time on the Percentage of Elongation of Steam Released and Steam Contained Polyester and Cotton Fabrics.

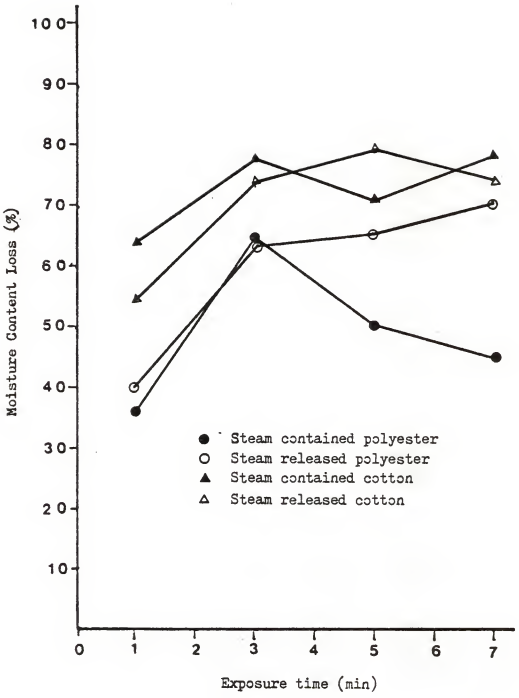

Figure 20. Effect of Exposure Time on the Percentage Moisture Content.

SUMMARY AND CONCLUSIONS

Two types of fabrics, polyester and cotton, were inoculated with Staphylococcus aureus, Escherichia coli, and Bacillus cereus. Samples of each fabric and bacteria type were exposed to microwave energy for 0, 1, 3, 5, and 7 minutes in a steam released and steam contained environment. The lethal effect of microwave energy was determined by removing the bacteria from the fabric samples and performing serial dilutions and plate counts. The tensile strength, percentage elongation and moisture content were determined for controls and for samples exposed to microwaves for each time interval and condition. The results may be summarized as follow:

1. Escherichia coli was the most suspectible to reduction by microwave energy and Bacillus cereus was the most resistant. Thus proving that textiles may be sanitized by microwaves only if spore forming organisms or spores are not present.

2. The sanitization potential of microwaves is not influenced by fiber type, or moisture content of textiles.

3. The optimum exposure time for microwave sanitization varied with each bacteria type and was never reached for Bacillus cereus spores.

4. Temperature was directly related to exposure time of microwave energy.

5. Cotton and polyester samples exposed in a steam released environment significantly increased in tensile strength.

6. Elongation properties of both fabric types were not significantly affected by microwaves.

7. The fabric condition or environment (released or contained steam) had a significant effect on moisture regain. Steam released samples reached the bone-dry state within seven minutes, thus making microwave energy an efficient method for textile drying.

RECOMMENDATIONS

This study has shown that vegetative cells can be eliminated by microwave energy within seven minutes and spores are reduced and may be eliminated in an excess of seven minutes. More research is needed in this area of study to determine if spores can be eliminated by longer exposure times and the feasibility of using larger objects such as, surgical gowns, linens, etc. Another interesting project would be to determine if the bacteria naturally found on hospital clothing and linens was more susceptible to microwaves than the laboratory nurtured inoculum. Another related area of study would be to determine if fungus, such as that which causes athlete's foot, could be eliminated by microwave energy.

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APPENDIX A

Raw Data

Table A1

Number of Viable Organisms after Steam Contained Microwave Exposure

Exposure Time (min)	Polyester		Cotton	
	Rep 1	Rep 2	Rep 1	Rep 2
Staphylococcus aureus				
0	1.5×10^5	1.2×10^6	9.4×10^4	2.1×10^5
1	1.4×10^5	6.0×10^5	9.4×10^4	1.4×10^5
3	2.0×10^3	0	1.6×10^4	1.4×10^4
5	0	2.5×10^2	7.8×10^3	2.5×10^2
7	0	2.5×10^2	5.0×10^2	2.5×10^2
Escherichia coli				
0	1.1×10^6	8.0×10^5	8.0×10^4	1.1×10^5
1	1.6×10^5	4.0×10^4	0	8.0×10^3
3	0	0	0	0
5	0	0	0	0
7	0	0	0	0

Table A2

Percent Reduction of Staphylococcus aureus in Steam Contained Microwave Exposure

Exposure (min)	Polyester		Temperature (°C)	Cotton		Temperature (°C)
	Rep 1	Rep 2		Rep 1	Rep 2	
0	0	0	NA*	0	0	NA*
1	6.2	50.0	66	0	33.3	66
3	98.6	100.0	77	82.4	93.6	88
5	100.0	99.9	104	91.8	99.9	104
7	100.0	99.9	121	99.5	99.9	121

* Not Available

Table A3

Percent Reduction of Escherichia coli in Steam Contained Microwave Exposure

Exposure (min)	Polyester		Temperature (°C)	Cotton		Temperature (°C)
	Rep 1	Rep 2		Rep 1	Rep 2	
0	0	0	NA*	0	0	NA*
1	85.5	95.0	66	100.0	92.7	66
3	100.0	100.0	77	100.0	100.0	88
5	100.0	100.0	104	100.0	100.0	104
7	100.0	100.0	121	100.0	100.0	121

* Not Available

Table A4.

Number of Viable Organisms after Steam Released Microwave Exposure

Exposure Time (min)	Polyester		Cotton	
	Rep 1	Rep 2	Rep 1	Rep 2
Staphylococcus aureus				
0	8.2×10^4	1.0×10^5	8.2×10^4	9.5×10^4
1	5.9×10^4	7.0×10^4	6.0×10^4	6.7×10^4
3	7.0×10^3	7.4×10^3	9.0×10^3	8.5×10^3
5	2.5×10^3	1.3×10^3	3.5×10^3	2.8×10^3
7	0	0	2.5×10^2	0
Escherichia coli				
0	3.8×10^4	6.4×10^4	4.5×10^4	8.0×10^4
1	1.0×10^4	9.3×10^3	0	0
3	0	0	0	0
5	0	0	0	0
7	0	0	0	0

Table A5

Percent Reduction of Staphylococcus aureus in Steam Released Microwave Exposure

Exposure Time (min)	Polyester		Temperature (°C)	Cotton		Temperature (°C)
	Rep 1	Rep 2		Rep 1	Rep 2	
0	0	0	NA*	0	0	NA*
1	27.6	29.0	54	26.8	30.0	60
3	91.4	92.6	85	89.0	91.0	77
5	96.9	98.7	110	95.7	97.0	104
7	100.0	100.0	121	99.7	100.0	121

*Not Available

Table A6

Percent Reduction of Escherichia coli in Steam Released Microwave Exposure

Exposure Time (min)	Polyester		Temperature (°C)	Cotton		Temperature (°C)
	Rep 1	Rep 2		Rep 1	Rep 2	
0	0	0	NA*	0	0	NA*
1	73.7	85.5	54	100.0	100.0	60
3	100.0	100.0	85	100.0	100.0	77
5	100.0	100.0	110	100.0	100.0	104
7	100.0	100.0	121	100.0	100.0	121

* Not Available

Table A7

Percent Reduction of Bacillus cereus in Steam Contained Microwave Exposure

Exposure Time (min)	Survivors after Microwave Exposure	Survivors after Heat Activation	Total Survivors	Reduction (%)
Polyester - Rep. 1				
0	6.4×10^{4}	5.1×10^{4}	1.2×10^{5}	
1	1.3×10^{5}	5.9×10^{4}	1.9×10^{5}	-64.35
3	9.9×10^{4}	3.8×10^{4}	1.4×10^{5}	-19.13
5	2.6×10^{5}	4.5×10^{3}	2.6×10^{5}	-54.07
7	2.0×10^{5}	1.1×10^{4}	2.2×10^{5}	-75.00
Polyester - Rep. 2				
0	2.9×10^{5}	3.9×10^{4}	3.3×10^{5}	
1	8.4×10^{4}	2.8×10^{4}	1.1×10^{5}	66.36
3	1.1×10^{5}	2.8×10^{4}	1.4×10^{5}	58.72
5	2.7×10^{5}	3.0×10^{3}	2.7×10^{5}	16.21
7	1.5×10^{5}	6.0×10^{3}	1.6×10^{5}	51.57
Cotton - Rep. 1				
0	9.7×10^{4}	8.5×10^{4}	1.8×10^{5}	
1	5.0×10^{5}	3.5×10^{4}	8.5×10^{5}	53.30
3	1.7×10^{5}	3.9×10^{4}	2.1×10^{5}	-13.74
5	1.2×10^{5}	3.7×10^{4}	1.6×10^{5}	13.74
7	7.9×10^{4}	3.1×10^{4}	1.1×10^{5}	39.56
Cotton - Rep. 2				
0	1.7×10^{5}	8.5×10^{4}	2.5×10^{5}	
1	2.1×10^{5}	6.2×10^{4}	2.7×10^{5}	-7.54
3	2.7×10^{5}	6.3×10^{4}	3.3×10^{5}	-31.75
5	2.2×10^{5}	4.5×10^{4}	2.6×10^{5}	-3.97
7	2.1×10^{5}	1.1×10^{4}	2.2×10^{5}	14.68

Table A8

Percent Reduction of Bacillus cereus in Steam Released Microwave Exposure

Exposure Time (min)	Survivors after Microwave Exposure	Survivors after Heat Activation	Total Survivors	Reduction (%)
Polyester - Rep. 1				
0	6.4×10^4	5.1×10^4	1.2×10^5	
1	1.5×10^5	4.6×10^4	2.0×10^5	-70.43
3	1.1×10^5	8.6×10^4	2.0×10^5	-73.04
5	1.4×10^5	1.1×10^5	2.5×10^5	-116.52
7	8.2×10^4	8.0×10^3	9.0×10^4	21.74
Polyester - Rep. 2				
0	2.9×10^5	3.9×10^4	3.3×10^5	
1	2.0×10^5	1.1×10^5	3.1×10^5	4.59
3	2.9×10^5	1.4×10^5	4.3×10^5	-31.80
5	3.1×10^5	7.8×10^4	3.9×10^5	-18.35
7	2.9×10^5	1.3×10^4	3.0×10^5	7.49
Cotton - Rep. 1				
0	9.7×10^4	8.5×10^4	1.8×10^5	
1	1.6×10^5	2.1×10^4	1.8×10^5	.55
3	7.6×10^4	5.7×10^4	1.3×10^5	26.92
5	9.0×10^4	6.1×10^4	$1,5 \times 10^5$	17.03
7	2.2×10^4	2.1×10^4	4.3×10^4	76.37
Cotton - Rep. 2				
0	1.7×10^5	8.5×10^4	2.5×10^5	
1	2.5×10^5	1.5×10^5	4.0×10^5	-57.94
3	2.4×10^5	9.7×10^4	3.3×10^5	-31.75
5	2.1×10^5	2.7×10^5	4.8×10^5	-88.88
7	2.0×10^4	8.5×10^4	1.1×10^5	58.33

Table A9

Strength and Elongation of Microwave Exposed Polyester and Cotton

Exposure Time (min)	Dry				Wet			
	Strength, Kg		% Elongation		Strength, Kg		% Elongation	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Polyester								
0	51.42	51.17	35.50	35.01	51.42	51.17	35.50	35.01
1	51.58	52.63	35.50	35.01	50.25	50.08	35.01	35.01
3	47.75	49.25	35.50	35.01	52.75	51.50	35.50	35.01
5	50.00	49.92	35.50	35.50	50.25	52.25	35.01	35.50
7	48.50	51.33	35.01	34.52	48.42	50.67	35.01	35.01
Cotton								
0	23.04	23.25	11.44	11.30	23.04	23.25	11.44	11.30
1	24.71	23.38	11.44	11.71	21.50	21.73	11.57	11.44
3	21.65	22.75	11.57	11.17	21.59	20.96	11.57	11.44
5	22.04	20.84	11.17	11.30	20.84	20.67	11.57	11.30
7	22.04	20.59	11.44	11.30	21.96	22.25	11.40	11.57

Table A10

Percent Moisture Regain of Polyester and Cotton in Steam Contained Microwave Exposure

Exposure Time (min)	Wet Weight (g)	Microwaved Weight (g)	Bone-dry Weight (g)	Percent Moisture Regain		
				Wet Samples	Microwaved Samples	Difference
Polyester - Rep 1						
1	.4846	.3690	.3390	42.95	8.85	34.10
3	.5090	.3260	.3057	66.50	6.64	59.86
5	.4614	.3480	.3085	49.56	12.80	36.76
7	.4400	.3470	.3102	41.84	11.86	29.98
Polyester - Rep 2						
1	.5324	.4113	.3264	63.11	26.01	37.10
3	.5393	.3192	.3189	69.11	.09	69.02
5	.5200	.3172	.3171	63.99	.03	63.96
7	.5198	.3195	.3195	62.69	.00	62.69
Cotton - Rep 1						
1	.5621	.4130	.2960	89.90	39.53	50.37
3	.5464	.3181	.2911	87.70	9.28	78.42
5	.4910	.2998	.2814	74.48	6.54	67.94
7	.5347	.2990	.2899	84.44	3.14	81.30
Cotton - Rep 2						
1	.5352	.3115	.2907	84.11	7.16	76.95
3	.5352	.3178	.2872	86.35	10.65	75.70
5	.5350	.3153	.2908	83.98	8.43	75.55
7	.5224	.3055	.2850	83.30	7.19	76.11

Table A11

Percent Moisture Regain of Polyester and Cotton in Steam Released Microwave Exposure

Exposure Time (min)	Wet Weight (g)	Microwaved Weight (g)	Bone-dry Weight (g)	Percent Moisture Regain		
				Wet Samples	Microwaved Samples	Difference
Polyester - Rep 1						
1	.4846	.3690	.3390	42.95	8.85	34.10
3	.5090	.3260	.3057	66.50	6.64	59.86
5	.4914	.3080	.3005	63.53	2.50	61.03
7	.4900	.3070	.3002	63.22	2.27	60.95
Polyester - Rep 2						
1	.5700	.4293	.3115	82.99	37.82	45.17
3	.5150	.3074	.3102	66.02	-.90	66.92
5	.5355	.3168	.3056	75.23	3.66	71.57
7	.5625	.3110	.3146	78.80	-1.14	79.94
Cotton - Rep 1						
1	.5044	.3473	.2922	72.62	18.86	53.76
3	.4830	.2880	.2859	68.94	.73	68.21
5	.4863	.2749	.2750	76.84	-.04	76.88
7	.4903	.2845	.2845	72.33	.00	72.33
Cotton - Rep 2						
1	.4535	.3110	.2569	76.53	21.06	55.47
3	.4540	.2550	.2524	79.87	1.03	78.84
5	.4586	.2539	.2488	84.32	2.05	82.27
7	.4516	.2570	.2605	73.36	-1.34	74.70

APPENDIX B

Data Analysis

Table B1

Analysis of Variance for Percent Reduction of Staphylococcus aureus

Source of Variation	Degrees of Freedom	Anova Sum of Squares	F	PR>F
Exposure (E)	3	29518.068	24.94	.001*
Fabric (F)	1	47.045	.12	.734
Condition (C)	1	380.880	.97	.340
E x F	3	540.033	.46	.717
E x C	3	569.248	.48	.700
F x C	1	87.120	.22	.645
E x F x C	3	631.293	.53	.666
Total	15			

* 0.01 level of significance.
Exposure: 0, 1, 3, 5, 7 minutes
Fabrics: polyester and cotton
Condition: steam released and contained

Table B2

Duncan's Multiple Range Test for Interaction of Exposure Level and Percent Reduction of Staphylococcus aureus

Exposure (minutes)	Grouping*	Means ranked
7	A	99.875
5	A	97.313
3	A	80.775
1	B	24.588

*Means with the same letter are not significantly different.

Table B3

Analysis of Variance for Percent Reduction of Bacillus Cereus

Source of Variation	Degrees of Freedom	Anova Sum of Squares	F	PR>F
Exposure (E)	3	17100.052	1.62	0.224
Fabric (F)	1	1045.502	0.30	0.593
Condition (C)	1	7759.194	2.21	0.157
E x F	3	7504.192	0.71	0.559
E x C	3	4251.521	0.41	0.753
F x C	1	96.640	0.03	0.870
E x F x C	3	5575.683	0.53	0.669
Total	15			

*0.01 level of significance
Exposure: 0, 1, 3, 5, 7 minutes
Fabric: polyester and cotton
Condition: steam released and contained

Table B4

Analysis of Variance for Percent Change in Tensile Strength of Microwaved Exposed Polyester and Cotton Fabrics

Source of Variation	Degrees of Freedom	Anova Sum of Squares	F	PR>F
Exposure (E)	3	88.651	3.60	.037*
Fabric (F)	1	126.127	15.35	.001*
Condition (C)	1	10.114	1.23	.284
E x F	3	43.660	1.77	.193
E x C	3	100.342	4.07	.025*
F x C	1	45.864	5.58	.031*
E x F x C	3	61.516	2.50	.096
Total	15			

* 0.01 level of significance
Exposure: 0, 1, 3, 5, 7 minutes
Fabrics: polyester and cotton
Condition: steam released and contained

Table B5

Duncan's Multiple Range Test for Interaction of Exposure Level and Percent Change in Tensile Strength

Exposure (minutes)	Grouping*	Means Ranked
5	A	5.099
7	A	4.621
3	A	4.000
1	B	0.836

* Means with the same letter are not significantly different.

Table B6

Duncan's Multiple Range Test for Interaction of Fabric and Percent Change in Tensile Strength

Fabric	Grouping*	Means Ranked
Cotton	A	5.624
Polyester	B	1.653

*Means with the same letter are not significantly different.

Table B7

Duncan's Multiple Range Test for Interaction of Exposure Level, Condition, and Percent Change in Tensile Strength

Exposure (minutes)	Condition	Grouping*	Means Ranked
7	released	A	5.203
5	contained	A	5.215
5	released	A	4.983
3	released	B	4.768
1	contained	A	4.408
7	contained	A	3.950
3	contained	A	3.233
1	released	B	2.735

* Means with the same letter are not significantly different.

Table B8

Duncan's Multiple Range Test for Interaction of Fabric, Condition, and Percent Change in Tensile Strength

Fabric	Condition	Grouping*	Means Ranked
Cotton	contained	A	7.384
Cotton	released	A	3.865
Polyester	released	B	2.289
Polyester	contained	B	1.019

* Means with the same letter are not significantly different.

Table B9

Analysis of Variance for Percent Change in Elongation of Microwave Exposed Polyester and Cotton Fabrics

Source of Variation	Degrees of Freedom	Anova Sum of Squares	F	PR>F
Exposure (E)	3	0.193	1.00	0.418
Fabric (F)	1	0.209	3.26	0.090
Condition (C)	1	0.004	0.06	0.810
E x F	3	0.416	2.16	0.133
E x C	3	0.136	0.70	0.563
F x C	1	0.055	0.86	0.368
E x F x C	3	0.072	0.37	0.773
Total	15			

* 0.01 level of significance
Exposure: 0, 1, 3, 5, 7 minutes
Fabric: polyester and cotton
Condition: steam released and contained

Table B10

Analysis of Variance for Moisture Regain

Source of Variation	Degrees of Freedom	Anova Sum of Squares	F	PR>F
Exposure (E)	3	2331.494	7.11	0.003 *
Condition (C)	1	136.910	1.25	0.279
Fabric (F)	1	2308.431	21.13	0.000 *
E x F	3	347.641	1.06	0.393
E x C	3	105.339	0.32	0.810
F x C	1	350.794	3.21	0.092
E x F x C	3	199.968	0.61	0.618
Total	15			

* 0.01 level of significance
Exposure: 0, 1, 3, 5, 7 minutes
Fabric: polyester and cotton
Condition: steam released and contained

Table B11

Duncan's Multiple Range Test for Interaction of Exposure Level and Percent Change in Moisture Regain

Exposure (minutes)	Grouping*	Means Ranked
3	A	69.604
7	A	67.250
5	A	66.995
1	B	48.378

*Means with the same letter are not significantly different.

MICROWAVE SANITIZATION OF SELECTED TEXTILES

by

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AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

The sanitization and drying potential of 2450 MHz microwave radiation on polyester and cotton fabrics was evaluated using Staphylococcus aureus, Escherichia coli, and Bacillus cereus spores. Bacillus cereus spores were the most tolerant microorganisms to microwave radiation and Escherichia coli was the most sensitive. A reduction of 100% was obtained with Staphylococcus aureus and Escherichia coli within seven minutes of exposure to microwave radiation. Fabric conditions of steam released and steam contained did not affect the amount of bacterial reduction. A linear relationship was found between temperature and percentage reduction which indicated a temperature dependent reduction. The efficiency of microwave drying was proven when the time to reach the bone-dry weight of the fabrics was compared to that required in convection heating.

Fabric strength and elongation were evaluated before and after microwave exposure. Microwave heating did not have an effect on elongation properties, but the tensile strength of both the polyester and cotton fabrics was increased between one and three minutes in a steam released enviroment.